Designation: F 1530 – 94

Standard Test Method for Measuring Flatness, Thickness, and Thickness Variation on Silicon Wafers by Automated Noncontact Scanning [1]

This standard is issued under the fixed designation F 1530; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers a noncontacting, nondestructive procedure to determine the thickness and flatness of clean, dry, semiconductor wafers in such a way that no physical reference is required.

1.2 This test method is applicable to wafers 50 mm or larger in diameter, and 100 µm (0.004 in.) approximately and larger in thickness, independent of thickness variation and surface finish, and of wafer shape.

1.3 This test method measures the flatness of the front wafer surface as it would appear relative to a specified reference plane when the back surface of the water is ideally flat, as when pulled down onto an ideally clean, flat chuck. It does not measure the free-form shape of the wafer.

1.4 Because no chuck is used as a measurement reference, this test method is relatively insensitive to microscopic particles on the back surface of the wafer.

1.5 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

F 1241 Terminology of Silicon Technology [2]

F 1390 Test Method for Measuring Warp on Silicon Wafers by Automated Noncontact Scanning [2]

2.2 *SEMI Standard:*

M1 Specifications for Polished Monocrystalline Silicon Wafers [3]

3. Terminology

3.1 Definitions and acronyms related to wafer flatness may be found in SEMI Specifications M 1.

3.2 Other definitions relative to silicon material technology can be found in Terminology F 1241.

4. Summary of Test Method

4.1 A calibration procedure is performed. This sets the instrument's scale factor and other constants.

4.2 The wafer is supported by a small-area chuck and is scanned along a prescribed pattern by both members of an opposed pair of probes.

4.3 The paired displacement values are used to construct a thickness data array ($t[x,y]$). This array represents the front surface of the wafer when the back surface of the wafer is ideally flat, as when pulled down onto and ideally clean, flat chuck (see figures in Appendix X1).

4.4 The data array is used to produce one or more of the parameters required by the application.

4.4.1 If flatness measurements are required, a reference plane and a focal plane suitable to the application are constructed on the back or front surface as described in Appendix X2.

4.5 Thickness or flatness, or both values are calculated and reported as required.

5. Significance and Use

5.1 Flatness, thickness and thickness variation are vital factors affecting the yield of semiconductor device processing.

5.2 Knowledge of these characteristics can help the producer and consumer determine if the dimensional characteristics of a specimen wafer satisfy given geometrical requirements.

5.3 This test method is suitable for measuring the flatness and thickness of wafers used in semiconductor device processing in the as-sliced, lapped, etched, polished, epitaxial or other layer condition.

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[1] This test method is under the jurisdiction of ASTM Committee F-1 on Electronicsand is the direct responsibility of Subcommittee F01.06 on Silicon Materials and Process Control.

Current edition approved July 15, 1994. Published September 1994.

[2] *Annual Book of ASTM Standards*, Vol 10.05.

[3] Available from Semiconductor Equipment and Materials International, 805 East Middlefield Rd., Mountain View, CA 94043.

5.4 Until the results of a planned interlaboratory evaluation of this test method are established, use of this test method for commercial transactions is not recommended unless the parties to the test establish the degree of correlation that can be obtained.

6. Interferences

6.1 Any relative motion between the probes and along the probe measuring axis during scanning will produce error in the lateral position equivalent-measurement data.

6.2 Most equipment systems capable of this measurement have a definite range of wafer thickness combined with sori/warp (dynamic range) that can be accommodated without readjustment. If the sample moves outside this dynamic range during either calibration or measurement, results may be in error. An overrange signal can be used to alert the operator and measurement data examiners to this event.

6.3 The quantity of data points and their spacing may affect the measurement results (see 7.1.2).

6.4 Site flatness measurements may be affected if the site boundaries and corners do not contain data array elements. This effect may be reduced through interpolation techniques.

7. Apparatus

7.1 *Measuring Equipment*, consisting of wafer-holding device, multiple-axis transport mechanism, probe assembly with indicator, and system controller/computer, including data processor and suitable software. The system shall be equipped with an overrange signal. Instrument data reporting resolution shall be 10 nm or smaller.

7.1.1 *Wafer-Holding Device*, for example a chuck whose face is perpendicular to the measurement axis, and on which the wafer is placed for the measurement scan. The diameter of the wafer holding device shall be 0.9-in. (22-mm) diameter, 1.3-in. (33-mm) diameter, or other value as agreed upon between participating parties.

7.1.2 *Multiple-Axis Transport Mechanism*, which provides a means for moving the wafer-holding device, or the probe assembly, perpendicularly to the measurement axis in a controlled fashion in several axes. This motion must permit data gathering over a prescribed scan pattern within the entire quality area. Data point spacing shall be 2 mm or less, or other value as agreed upon between participating parties.

7.1.3 *Probe Assembly with Paired Noncontacting Displacement-Sensing Probes, Probe Supports, and Indicator Unit* —The probes shall be capable of independent measurement of the distance between the probe site on each surface of the sample wafer and the motion plane. The probes shall be mounted above and below the wafer in a manner so that the probed site on one surface of the wafer is opposite the probed site on the other. The common axis of these probes is the measurement axis (see Fig. 1). The probe separation D shall be kept constant during calibration and measurement. Displacement resolution shall be 10 nm or better. The probe sensor size shall be 4 × 4 mm, or other value to be agreed upon between participating parties.

7.1.3.1 The following equations are derived from Fig. 1. They are used in subsequent calculations as noted.

$$D = a + t + b \quad (1)$$

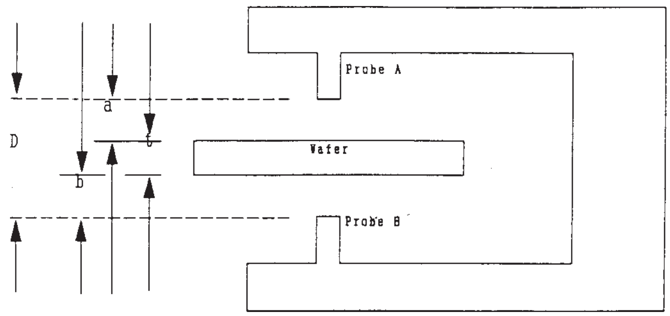


FIG. 1 Schematic View of Wafer, Probes, and Fixture

$$t = D - (a + b) \quad (2)$$

where:

D = the distance between Probes A and B,
a = the distance between Probe A and the nearest wafer surface,
b = the distance between Probe B and the nearest wafer surface, and
t = wafer thickness.

8. Materials

8.1 *Set-up Masters*, suitable to accomplish calibration and standardization as recommended by the equipment manufacturer.

8.2 *Reference Wafer*, with total thickness variation (TTV) value and flatness value similar to the product or process to be monitored and with a data set that is used to determine the level of agreement between the data set obtained by the system under test and the reference wafer data set (see Annex A1).

9. Suitability of Test Equipment

9.1 The suitability of the test equipment shall be determined with the use of a reference wafer and its associated data set in accordance with the procedures of Annex A1, or by performance of a statistically-based instrument repeatability study to ascertain whether the equipment is operating within the manufacturer's stated specification for repeatability.

NOTE 1—Subcommittee F1.95 is currently developing an instrument repeatability study format.

10. Sampling

10.1 This test method is nondestructive and may be used on either 100 % of the wafers in a lot or on a sampling basis.

10.1.1 If samples are to be taken, procedures for selecting the sample from each lot of wafers to be tested shall be agreed upon between the parties to the test, as shall the definition of what constitutes a lot.

11. Calibration and Standardization

11.1 Calibrate in accordance with the manufacturer's instructions.

12. Procedure

12.1 Prepare the apparatus for measurement of wafers, including selection of data display/output functions and fixed quality area (FQA) by specifying the nominal edge exclusion X.

12.1.1 *Measurement Method*—Global Flatness (*G*) or Site Flatness (*S*):

12.1.1.1 If *S* is chosen, then also specify site array details:

(*1*) site size,

(*2*) location of sites relative to FQA center,

(*3*) location of sites relative to each other, rectilinear or tiled pattern, and

(*4*) partial sites, included or excluded.

12.1.2 *Reference Surface*—front or back.

12.1.3 *Reference Plane and Area*:

12.1.3.1 For Global Flatness Measurements, Global Reference Plane:

(*1*) Ideal backside plane construction, or

(*2*) Three-point frontside plane construction, or

(*3*) Least-squares frontside plane construction.

12.1.3.2 For Site Flatness Measurements, Global Reference Plane:

(*1*) Ideal backside plane construction, or

(*2*) Three-point frontside plane construction, or

(*3*) Least-squares frontside plane construction.

12.1.3.3 For Site Flatness Measurements, Site Reference Plane:

(*1*) Site least-squares plane construction.

12.1.4 *Measurement Parameter*:

12.1.4.1 Global Flatness:

(*1*) Total indicator reading, (TIR) or

(*2*) Focal plane deviation, (FPD).

12.1.4.2 Site Flatness:

(*1*) TIR—each site or maximum value for all sites, or both, or

(*2*) FPD—each site or maximum value for all sites, or both, or

(*3*) Distribution of these values.

12.2 Introduce the test specimen into the measurement mechanism and initiate the measurement sequence.

13. Calculations

13.1 The instrument is assumed to be direct reading with all necessary calculations performed internally and automatically as follows:

13.1.1 The displacements (distances) between each probe and the nearest surface of the wafer are determined (in pairs) at intervals along the scan pattern. At each measurement location, the sum of the displacements is subtracted from *D*, yielding the thickness as follows:

$$t = D - (a + b) \tag{3}$$

13.1.2 A data array whose elements are the thicknesses ($t[x,y]$) is constructed.

13.1.3 Reference and focal planes for flatness calculation are constructed as described in Annex A1.

13.2 Calculate thickness and flatness as required by the application as follows:

13.2.1 *Total Thickness Variation*:

$$TTV = t_{max} - t_{min}. \tag{4}$$

13.2.2 *Global Flatness*:

where:

$f(x,y)$ = $t(x,y) - (d_F x + b_F y + c_F)$, and x,y range over the FQA,

GBIR, *GF3R* and *GFLR* = $f(x,y)_{max} - f(x,y)_{min}$, and

GF3D and *GFLD* = the larger of $|f(x,y)_{max}|$ or $|f(x,y)_{min}|$.

NOTE 2—GBIR equals TTV.

13.2.3 *Site Flatness*:

where:

$f(x,y)$ = $t(x,y) - (d_F x + b_F y + c_F)$, and x,y range over the site,

SF3R, SFLR, SFQR and *SBIR* = $f(x,y)_{max} - f(x,y)_{min}$, and

SF3D, SFLD, SLQD and *SBID* = the larger of $|f(x,y)_{max}|$ or $|f(x,y)_{min}|$.

13.3 Record the calculated values.

13.4 For referee or other measurements where the wafer is measured more than once, calculate the maximum, minimum, sample standard deviation, average and range of all measurements on the sample.

14. Report

14.1 Report the following information:

14.1.1 Date, time, and temperature of test,

14.1.2 Identification of operator,

14.1.3 Identification of measuring instruments, including wafer-holding device diameter, data point spacing, sensor size, and measurement method,

14.1.4 Lot identification, including nominal diameter and nominal center point thickness,

14.1.5 Description of sampling plan, and one or more of the following parameters as required by the application:

14.1.6 Centerpoint thickness of each wafer measured,

14.1.7 Thickness variation of each wafer measured,

14.1.8 Flatness of each wafer measured, described as one or more of the following choices:

14.1.8.1 The global flatness, or

14.1.8.2 The maximum value of site flatness as measured on all sites, or

14.1.8.3 The percentage of sites which have a site flatness ≤ a specified value, and

14.1.9 Distribution of all sites on all wafers measured, when site flatness is measured.

14.2 For referee tests the report shall also include the standard deviation of each set of wafer measurements.

15. Precision and Bias

15.1 *Precision*—A single laboratory precision test of this test method produced the following results:

15.1.1 A single automatic test system, reported to be in statistical control according to internal records, was calibrated with NIST-traceable thickness masters.

15.1.2 Twenty four (24) samples of 150-mm nominal diameter single-side polished silicon wafers, all with 675-µm nominal thickness, and with bow ranging from 1.380 to 52.238 µm and with warp ranging from 8.852 to 53.182 µm, were first run through the test system to produce a set of graphical printouts, with contour plots, for later analysis. Next the system ran multiple cassette-cassette "passes": two passes were run on each of three successive business days, for a total of six passes. These samples and their base data set were used in an interlaboratory experiment to test interlaboratory bow and warp repeatability and reproducibility on Test Method F 1390.

15.1.3 The six-pass data set included information on the following measurement parameters on each of the wafers:

Thickness:	Centerpoint, Maximum, Minimum, Average
Flatness, Global:	TTV (Total Thickness Variation)
	GFLD ($Global_{front, least-squares}$ Focal Plane $Deviation_{max}$)
	GFLR ($Global_{front, least-squares}$ Focal Plane Range)
	GF3D ($Global_{front, 3-point}$ Focal Plane $Deviation_{max}$)
	GF3R ($Global_{front, 3-point}$ Focal Plane Range)
Flatness, Site:	$SBIR_{max}$($Site_{back, ideal}$ Focal Plane Range (max of all sites))
	$SBID_{max}$($Site_{back, ideal}$ Deviation (max of all sites))

15.1.4 The 6-pass, 24-wafer data produced estimates of single laboratory precision (assumed equal to the average standard deviation) for each of the parameters as shown in Table 1:

15.1.5 Additional laboratories are participating in the test, and multi-laboratory data will be published.

15.2 *Bias*—No standards exist against which the bias of this test method can be evaluated.

TABLE 1 Single Laboratory Test Summary

Parameter		Average Standard Deviation σ_{n-1}, (µm)	Parameter Range (6-pass average)	
			Min, (µm)	Max, (µm)
Thickness	Centerpoint	0.058	669.12	683.06
	TTV	0.012	1.98	9.32
Global Flatness	GFLD	0.007	0.412	2.977
	GFLR	0.009	0.710	3.628
	GF3D	0.007	0.487	2.512
	GF3R	0.011	0.828	4.532
Site Flatness	SBID	0.008	0.347	2.133
	SBIR	0.008	0.587	2.938

NOTE 3—Subcommittee F1.95 is in the process of developing methods for producing related reference materials that can be used to certify the wafer artifacts.

16. Keywords

16.1 flatness; noncontact measurement; semiconductor; silicon; thickness; thickness variation; wafers

ANNEX

(Mandatory Information)

A1. COMPARING DATA SETS

A1.1 Introduction

A1.1.1 In qualifying a measurement system for operation, it can be useful to compare the values ascribed to an artifact such as a reference standard against those obtained for that artifact on a machine under test. This Annex outlines a way in which the multiple measurement data points that generate a single-value quantity of sori can be used to monitor the effects of interferences more informatively than by using that single-value alone.

A1.1.2 A data set is that set of data used in computation of sori. It is corrected data, that is, all possible after interferences have been removed and the data replanarized in accordance with the test method.

A1.1.3 A referee wafer (artifact) is accompanied by its own data set, referee data set (RDS), in which each data point is the average of a number of values obtained for that point over a number of "passes" (repeat measurements). The artifact is measured on a machine under test and its RDS is compared against the resultant-measured sample data set. Delta-point, delta-sori and other values are computed from the differences. The parameter used to determine agreement between the artifact and the system under test and the acceptable level of this agreement is to be agreed upon between the participating parties.

A1.2 Summary of Test Method

A1.2.1 Select a referee wafer of appropriate criteria, for which you have a referee data set (RDS).

A1.2.2 Measure the referee wafer on the machine under test to obtain a sample data set (SDS).

A1.2.3 Subtract the two to obtain a difference data set (DDS):

$$RDS - SDS = DDS \quad (A1.1)$$

A1.2.4 The DDS represents the differences between the measurements made on the machine under test and the referee data set. The DDS contains many values. The simplest metric that can be used to determine acceptability is maximum difference, the largest absolute value in the DDS. This represents the worst-case disagreement between the machine under test and the referee data.

A1.2.5 Accept the machine as suitable for measurement if the maximum difference is less than a value that is agreed upon between the parties to the test.

A1.2.6 More complex calculations may also be used, for example, a histogram of the (point-by-point) values of the DDS along with statistical measures (mean, sigma, etc.) may be compared. These measures can be compared to application-specific limits or used to provide insight into the nature and source of the difference, or both.

APPENDIXES

X1. VISUALIZATION OF THICKNESS, THICKNESS VARIATION AND GLOBAL FLATNESS

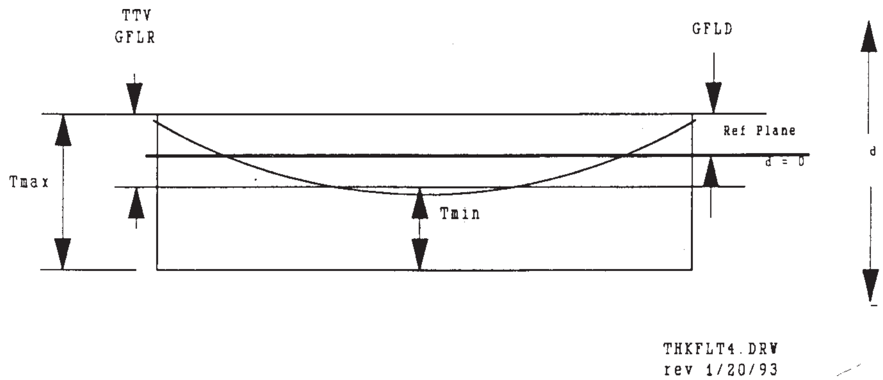
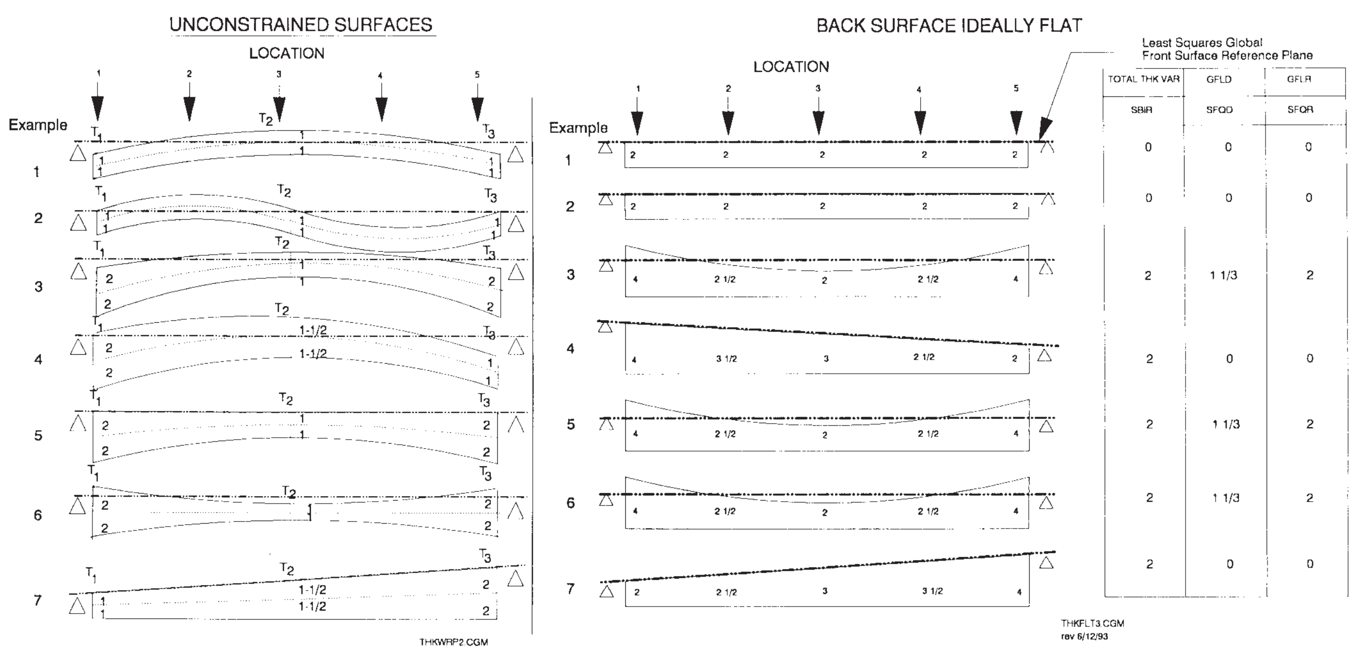


FIG. X1.1 Visualization of Thickness, Thickness Variation and Flatness

X1.1 To calculate flatness for a given case, it may be convenient to transform the measurement geometry and to consider the distance between the upper surface of the wafer and a reference plane as d, taken to be positive above the plane and negative below, as indicated in the example in Fig. X1.1.

X1.2 See Fig. X1.2 for examples of wafers with stylized thickness variation. Sample 3 in Fig. X1.2 represents the example below. Calculations for TTV and Global Flatness of each of these examples is given in Table X1.1.



NOTE 1—The above are stylized examples of wafers in an unconstrained state and with their back surfaces ideally flat. T_1 is 2 units, T_2 is 4 units, and T_3 is 3 units; the TTV and Flatness values are calculated from equations in 13.2. The individual measured distances and the calculated differences are shown in Table X1.1.

FIG. X1.2 Visualization of Thickness, TTV and Flatness—Stylized Examples

TABLE X1.1 Values for Figure X1.2

Example	Location	Values				
		Thickness	Thickness Center Point	Thickness Variation	Flatness GFLD	Flatness GFLR
1	1	2	2	0	0	0
	2	2				
	3	2				
	4	2				
	5	2				
2	1	2	2	0	0	0
	2	2				
	3	2				
	4	2				
	5	2				
3	1	4	2	2	1⅓	2
	2	3¼				
	3	2				
	4	3¼				
	5	4				
4	1	4	3	2	0	0
	2	3¾				
	3	3				
	4	2¾				
	5	2				
5	1	4	2	2	1⅓	2
	2	3½				
	3	2				
	4	3½				
	5	4				
6	1	4	2	2	1⅓	2
	2	3½				
	3	2				
	4	3½				
	5	4				
7	1	2	3	2	0	0
	2	2½				
	3	3				
	4	3½				
	5	4				

(Nonmandatory Information)

X2. Noncontact Thickness-based Flatness Measurement

X2.1 Thickness Data

X2.1.1 A thickness data set ($t[x,y]$) is the basis on which flatness calculations are made.

X2.2 Flatness Parameters

X2.2.1 There exist a variety of flatness measurements appropriate to different lithographic applications. These measurements are defined by four parameters as follows:

Parameter	Selections
(1) Measurement Method	Global or Site
(2) Reference Surface	Back or Front Side
(3) Reference Plane and Area	Global or Site Ideal, Least-squares, or 3-point
(4) Measurement Parameters	Range or Deviation

X2.2.2 The fixed quality area within which measurement data are to be taken and site size and array information when applicable must be specified.

X2.3 Measurement Calculations

X2.3.1 *Reference Plane Construction*:

X2.3.1.1 Construct a reference plane from the thickness data array $t(x,y)$. The reference plane is of the form as follows:

$$Z_{\text{Ref}} = a_R x + b_R y + c_R, \tag{X2.1}$$

where:
a_R, b_R, and c_R are chosen as follows:

For Ideal Back Surface Type of the Reference Plane,

$$a_R = b_R = c_R = 0 \tag{X2.2}$$

For the Least Squares Reference Plane Type, select a_R, b_R, and c_R so that

$$\sum_{x,y} [t(x,y) - (a_R x + b_R y + c_R)]^2 \tag{X2.3}$$

is minimized over the FQA for global determination and over the site for site determination.
For the Three-point Reference Plane Type, a plane is constructed so that

$$t(x_1, y_1) = a_R x_1 + b_R y_1 + c_R, \text{ and}$$

$$t(x_2, y_2) = a_R x_2 + b_R y_2 + c_R, \text{ and}$$

$$t(x_3, y_3) = a_R x_3 + b_R y_3 + c_R, \quad (X2.4)$$

where:

x_1, y_1; x_2 y_2; and x_3, y_3 are equally spaced points located on a radius whose perimeter is located 3 mm from the edge of a nominal-diameter wafer.

X2.3.2 If a deviation measurement is desired, construct a focal plane of the form as follows:

$$Z_{Focal} = a_F x + b_F y + c_F \quad (X2.5)$$

where:

For a Global Focal Plane:

a_F = a_R, and
b_F = b_R, and
c_F = c_R.

For a Site Focal Plane:

a_F = a_R, and
b_F = b_R, and
c_F = $t(x,y) - (a_F x + b_F y)$,

where:

x,y are located at the site center.

X2.3.3 *Flatness Measurement Algorithms*:

X2.3.3.1 Calculate the focal plane deviation at point x,y as follows:

$$f(x,y) = t(x,y) - (a_F x + b_F y + c_F) \quad (X2.6)$$

with the following algorithm:

if $|f(x,y)\text{max}| \geq |f(x,y)_{\text{min}}|$
then Deviation = $f(x,y)_{\text{max}}$,
else Deviation = $f(x,y)_{\text{min}}$.

X2.3.3.2 Calculate Range (also called TIR) as follows:

$$f(x,y)_{\text{max}} - f(x,y)_{\text{min}} \quad (X2.7)$$

where:

x,y = the range over the FQA for global measurements, and x,y is over a site for site measurements, and
$f(x,y)_{\text{max}}$ = the largest (most positive) algebraic value of $f(x,y)$ over the specified range of x,y, and
$f(x,y)_{\text{min}}$ = the smallest (most negative) algebraic value of $f(x,y)$ over the specified range of x,y.